Fabricating BRDFs at High Spatial Resolution Using Wave Optics

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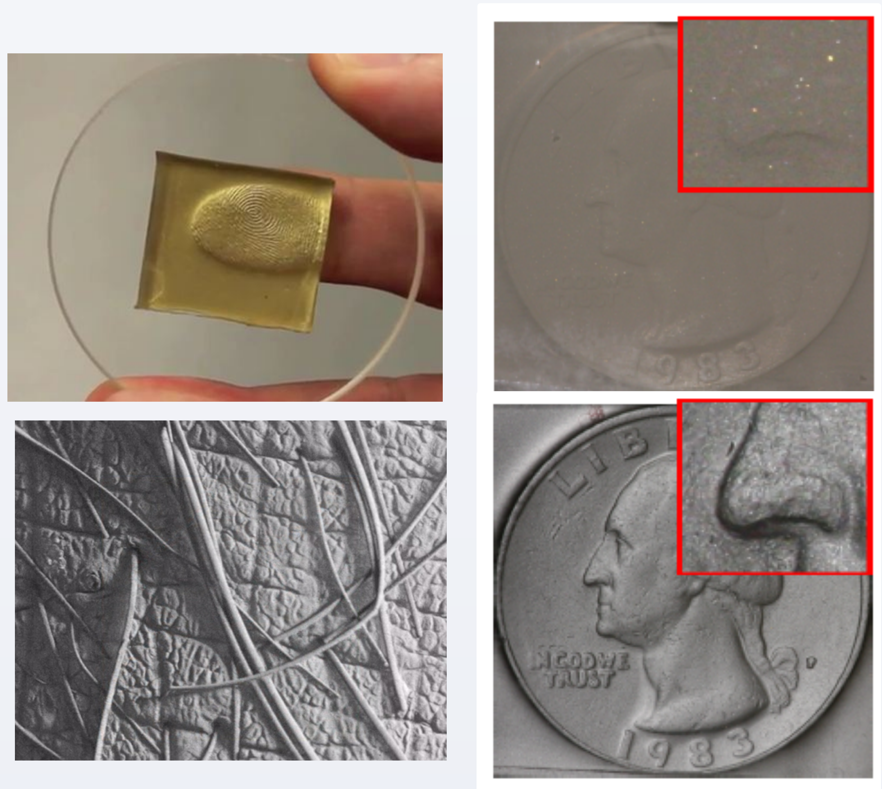
INTRODUCTION

We fabricate surfaces with controlled appearance and reflectance properties, which is important for many industrial applications, including printing, product design, luminaire design, security markers visible under certain illumination conditions, and many others.

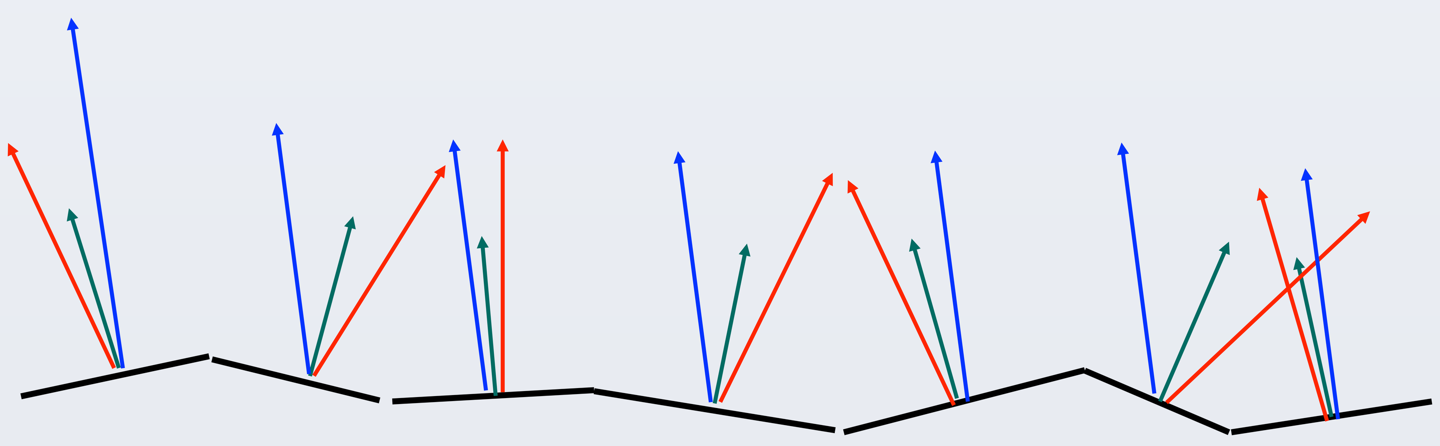
Pope's Revenge
(Berlin's TV tower)



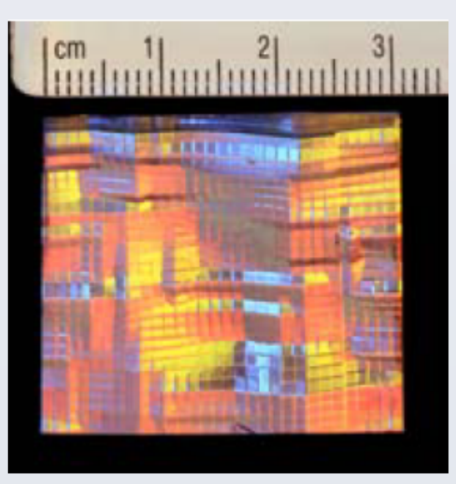
Gel Sight (Johnson & Adelson)

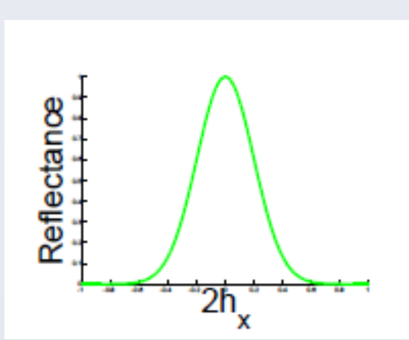
GEOMETRIC OPTICS V.S. WAVE OPTICS DESIGNS

Micro-facets model: The surface is composed of small mirror facets. Facets orientation determines the amount of energy reflected in different directions. (Weyrich et al. 09)

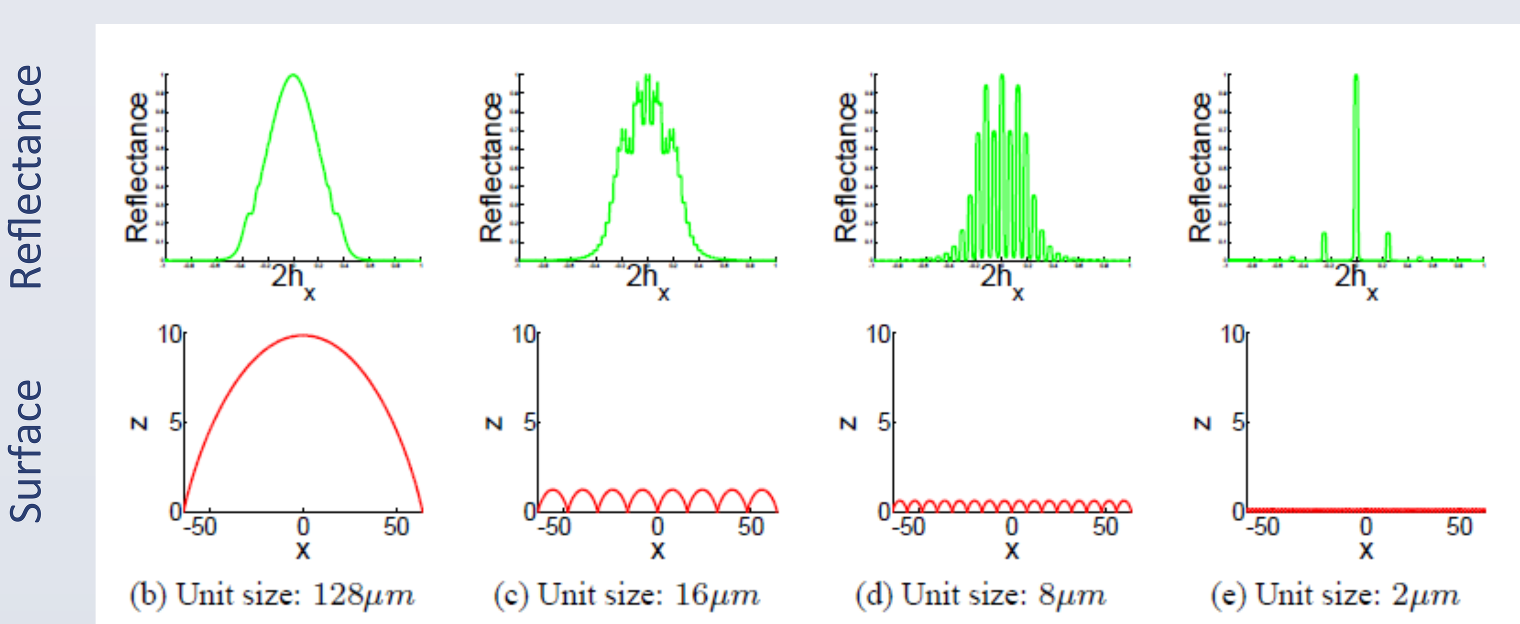


Limits of micro-facets model: cannot scale down the design since geometric optics model breaks. When facets size approach the wavelength, wave optics effects dominate. Typical dot size = 3cm x 3cm.





Target reflectance

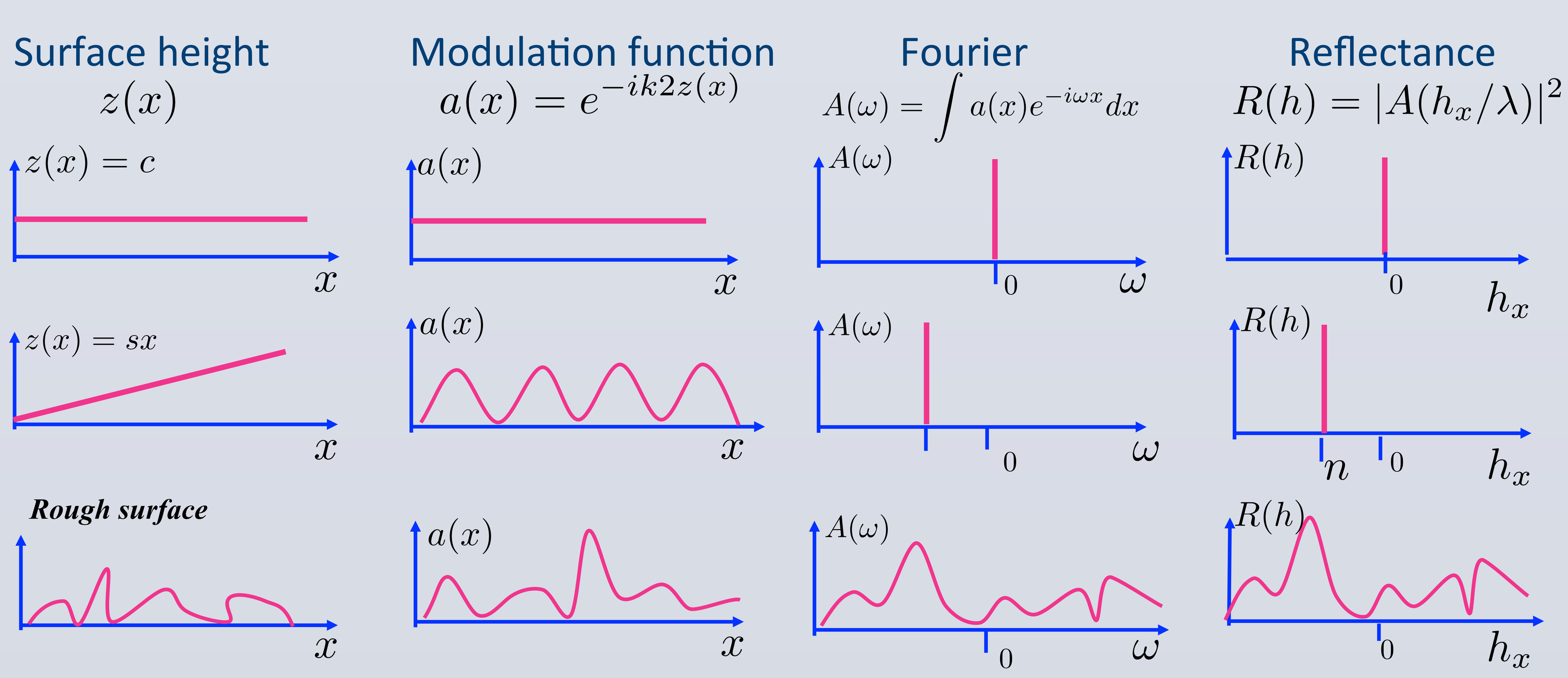


When surface scales down, the reflectance obtained is very different than the geometric optics prediction. To fabricate high resolution reflectance, our design accounts for wave optics effects.

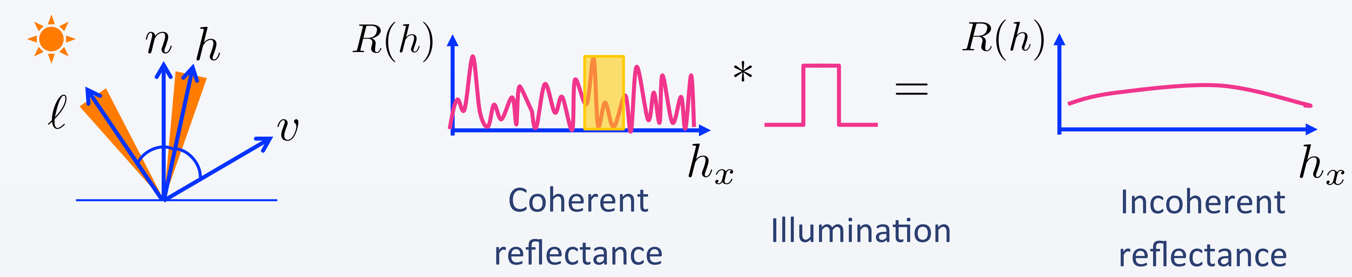
Existing BRDF fabrication: 3cm dot units. Our approach: 220dpi -> 0.1mm dot units.

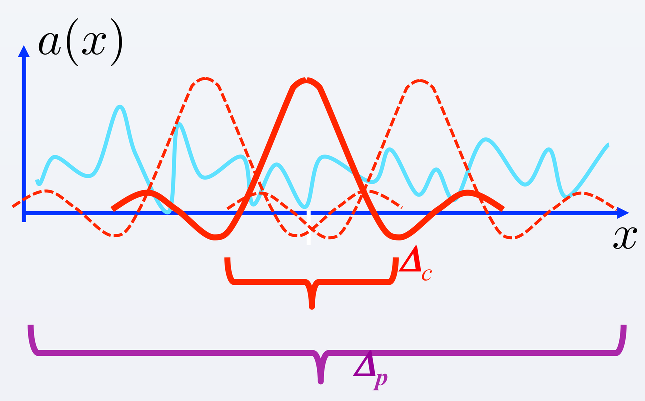
WAVE OPTICS THEORY OF SURFACE SCATTERING

1. Surface scattering with a point source (coherent illumination)



2. Surface scattering with an area source (incoherent illumination)





Resolution parameters:

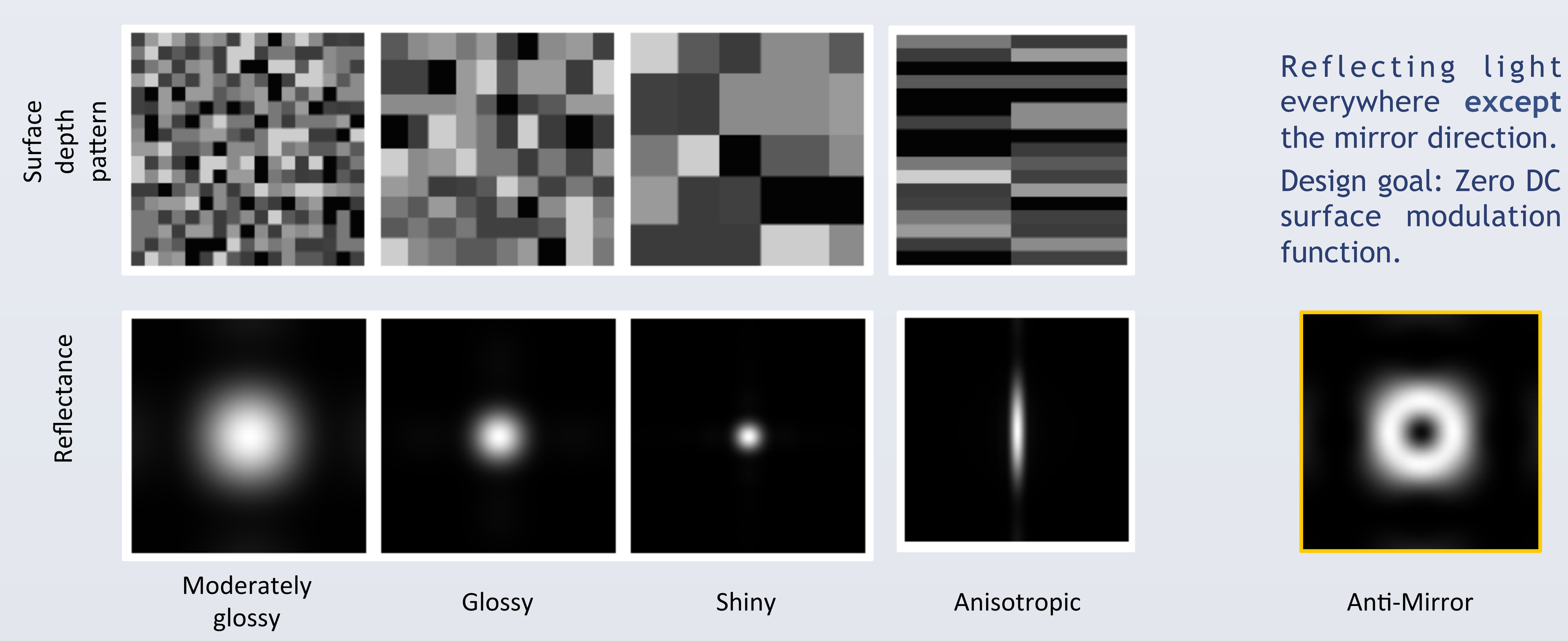
Dot (pixel) area: Δ_p Coherence area: Δ_c

Incoherent reflectance in primal: Fourier transform of each Δ_c structure, average **powers** of all Δ_c windows inside Δ_p.

REFLECTANCE DESIGN WITH MICRO FABRICATION

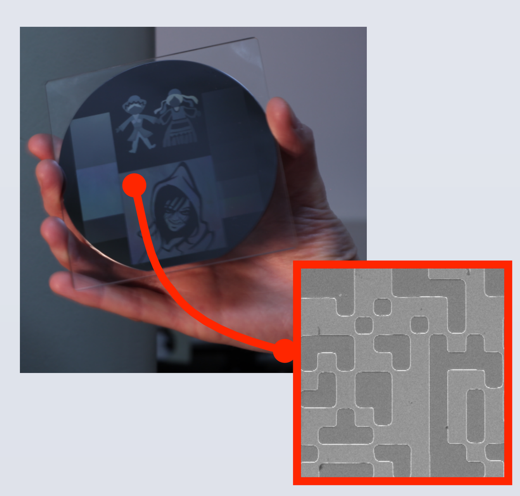
Photolithography uses light to transfer a geometric pattern from a photomask to a light-sensitive chemical photoresist on a substrate. Limitations: surface should be piecewise constant with a small number of depth layers.

- **Coherent Illumination**: find a surface height whose Fourier spectrum produce the desired reflectance.
- **Incoherence illumination**: find a set of Δ_c sized surface heights whose **averaged** Fourier power spectrum produce the desired reflectance.
  - **Sampling process**: step widths independently from a distribution p_a
  - **Primal**: sum of independent rectangles
    Expected spectrum: averaged sincs $E_{p_a}[a^2 \cdot \mathrm{sinc}^2(h_x/a^{-1})]$
  - Fourier sinc width inversely proportional to primal steps width.

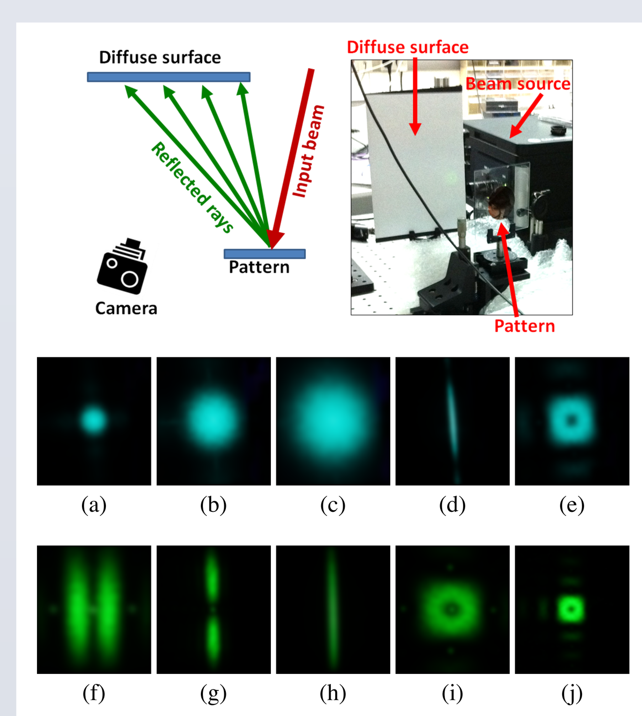


Reflecting light everywhere except the mirror direction.
Design goal: Zero DC surface modulation function.

FABRICATION RESULTS



A wafer fabricated using photo-lithography, with a spatial resolution of 220dpi. Each dot has a different BRDF.



Acquisition setup with the reflectance of a few patterns fabricated according to our approach.
(a-c): Glossy lobe of different widths;
(d,h): Anisotropic;
(e,i,j): Anti-mirrors;
(f-g): Anisotropic anti-mirrors.